Direct measurement of the jet geometry in Seyfert galaxies

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ABSTRACT

We demonstrate that, by combining optical, radio and X–ray observations of a Seyfert, it is possible to provide a direct measurement of the angle β between the direction of the radio jet and the normal to the plane of the spiral host galaxy. To do so, we make the assumptions that the inner radio jet is perpendicular to the X–ray observed inner accretion disk, and that the observed jet (or the stronger component, if the jet is two-sided) is physically closer to Earth than the plane of the galaxy. We draw attention to the possibility of measurement producing a result which is not self-consistent, in which case for that galaxy, one of the assumptions must fail.

Subject headings: accretion,accretion disks – galaxies:active – galaxies:jets – galaxies:Seyfert – galaxies:structure – X–rays:galaxies

1. Introduction

It might be expected, on grounds of symmetry and simplicity, that the jets emanating from a Seyfert nucleus would emerge at right angles to the disk of the host spiral galaxy. However, investigations of the observed *distribution* of the angle δ, the difference between the major axis of the galaxy and the radio jet (seen in projection on the plane of the sky) indicate that this is not the case (Ulvestad & Wilson 1984; Brindle et al. 1990; Baum et al. 1993; Schmitt et al. 1997). Clarke, Kinney & Pringle (1998; see also Kinney et al. 2000) have demonstrated that a reliable estimate of the *distribution* of the angle β between the jet axis and the normal to the galaxy plane can be obtained by considering, for each galaxy in the sample, the pair of values of δ and i, where i is the inclination of the galaxy to the line of sight (see Figure 1). They conclude that the directions of the radio jets are consistent with being completely uncorrelated with the planes of the host galaxies (see also Nagar & Wilson 1999).

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The study of this effect, which we suppose can be due to radiation induced warping of the accretion disk, or interactions of the host galaxy, is important for the understanding of the inner workings of Seyfert galaxies. Because we can only observe the galaxy and jet in projection on the plane of the sky, the measurements of δ and i merely restrict the jet axis to lie on the plane of a great circle, centered on the host nucleus, and do not provide a unique answer for β for each galaxy (Section 2.1). However, it has been shown (Nandra et al. 1997; Turner et al. 1998; Weaver & Reynolds 1998) that analysis of the shape of the Fe Kα line observed in the X–rays, can yield information on the inclination to the line of sight, $i_{\rm disk}$, of the inner accretion disk close to the central black hole, where the line is produced. We note here, that if one makes the additional assumption that the jet axis is perpendicular to the inner accretion disk then by measuring the three angles δ, i and $i_{\rm disk}$ it is possible to obtain a direct estimate of the angle β *for individual galaxies.*

2. Method for Determination of β

2.1. Geometry

For each galaxy we shall assume that we can determine three observational parameters, i, δ and $\phi = \pm i_{\rm disk}$. The angle i is the inclination of the plane of the galaxy to the plane of the sky, or equivalently the angle between the line of sight and the vector normal to the galaxy plane. The angle i lies in the range $0^\circ < i < 90^\circ$. We use a Cartesian coordinate system OXYZ based on the galaxy (see Clarke et al. 1998, and Figure 1). OX lies in the disk plane along the apparent major axis, OY lies in the disk along the apparent minor axis, and thus OZ is the vector normal to the galaxy plane. In these coordinates the unit vector in the direction of the line of sight is

$$\mathbf{k}_s = (0, -\sin i, \cos i). \tag{1}$$

The angle δ corresponds to the difference between the position angle of the apparent major axis of the galaxy and the direction of the radio jet projected onto the plane of the sky. By convention δ is taken to lie in the range $0^\circ < \delta < 90^\circ$.

For a given pair of values of δ and i, the direction of the jet, which we denote by a unit vector $\mathbf{k}_j$, is determined to lie on a great circle drawn on a unit sphere centered at the origin of our coordinate system. In the OXYZ coordinates described above the great circle is the set of points:

$$\mathbf{k}_j = (\cos\delta\sin\phi, \sin\delta\cos i\sin\phi - \sin i\cos\phi, \sin\delta\sin i\sin\phi + \cos i\cos\phi), \tag{2}$$

Here ϕ is the angle between the jet and the line of sight, that is, it is the angle between the vectors $\mathbf{k}_s$ and $\mathbf{k}_j$. Formally ϕ lies in the range $-180^\circ < \phi < 180^\circ$. [5]

[5]We should also note that there is a mirror symmetry to the problem about the apparent minor axis of the galaxy,

We can make the additional assumption that the observed jet (or the dominant jet, in the case of a two-sided jet) is the one that lies above the disk plane of the host galaxy (as seen from Earth), on the grounds that (apart from relativistic effects) free-free absorption in the galaxy plane and accretion disk will tend to obscure the counter-jet (e.g. Pedlar et al., 1998; see also Ulvestad et al., 1999). [6] This can also be determined from observations of HI 21cm absorption by the galaxy disk. In this case, the jet vector $\mathbf{k}_j$ is restricted to lying on one half of the great circle, and the full range of values of ϕ is not permitted. If we define β as the angle the jet vector $\mathbf{k}_j$ makes with the disk normal OZ (or $\hat{\mathbf{z}}$), then we see from Equation 2 that

$$\cos\beta = \mathbf{k}_j \cdot \hat{\mathbf{z}} = \sin\delta \sin i \sin\phi + \cos i \cos\phi. \tag{3}$$

Then the only permitted values of ϕ are those which give $0° < \beta < 90°$, or $\cos\beta > 0$. In terms of ϕ, this means that ϕ lies in the range $\phi_1 < \phi < \phi_1 + 180°$, where ϕ_1 (< 0) is the value of

$$\phi_1 = \tan^{-1}(-\cot i / \sin\delta), \tag{4}$$

which lies in the range $-90° < \phi_1 < 0°$. We note that physically, if $\phi < 0$, then the jet vector is projected against the half of the galaxy disk which is nearer to us, whereas $\phi > 0$ corresponds to the jet being projected against the half of the galaxy disk which is further from us.

2.2. Measurement of β

If, for a given galaxy, we have measurements of i (from the apparent ellipticity of the galaxy disk on the sky or from the fitting of kinematical data), of δ (from radio observations of the innermost jet structure) and of $i_{\rm disk} = \pm\phi$ (from modeling of the Fe Kα line from X-ray data, or by other means such as using H_2O maser information), then we can determine from Equation 3 two possible values for β, one for each sign of ϕ. The ambiguity between these values can be resolved by determining whether the observed jet lies in front of the near side ($\phi < 0$) or the far side ($\phi > 0$) of the galaxy. For most of the galaxies discussed here, inspection of the optical image shows unambiguously which side of the minor axis is nearer to us. The nearer side has distinct, dark dust lanes while the dust lanes on the further side cannot be seen because of the intervening bulge (Schmitt et al. 2000). When the dust lanes do not leave a distinct signature, we use the rotation curve of the galaxy together with the assumption that the spiral arms are trailing.

We give below some examples for which relatively well determined values of i, δ and $i_{\rm disk}$ are available.

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the OYZ plane, which means that reversing the direction of the OX axis leaves the problem unchanged. Thus, the sign of k_{jx} is not an observationally meaningful quantity, the jet vector in fact lies on one of two great circles which are reflections of each other in the OYZ plane, and we consider only one of them.

[6] There is still ambiguity in our knowledge of the relative position angles; here we assume that the dominant radio jet is between us and the plane of the galaxy, but we still may not know if the jet is projected against the half of the galaxy which is nearest to us or if it is projected against the half of the galaxy which is furthest from us.

2.2.1. Mrk 766 (NGC 4253)

This is a Seyfert 1 galaxy for which Kinney et al. (2000) find that $i = 31^\circ$ and $\delta = 35^\circ \pm 5^\circ$. Using ASCA observations of the Fe Kα line, Nandra et al (1997) have determined the inner disk inclination, $\pm\phi$, to be $i_{\rm disk} = 34^\circ \pm 3^\circ$, assuming that the disk is around a Schwarzschild black hole, or $i_{\rm disk} = 36^\circ\,{}^{+8}_{-7}$ for a maximal Kerr black hole. For simplicity we shall just make use of the values for the Schwarzschild black hole. Inspection of the HST image of Mrk 766 (Malkan et al. 1998) suggests that the radio jet (position angle 32°, Nagar et al. 1999) is seen in projection against the near side of the galaxy. Using the values given above together with this knowledge of orientation in Equation 3, we conclude that $\beta \simeq 57^\circ$.

2.2.2. NGC 2110

This is a Seyfert 2 galaxy for which Nagar & Wilson (1999) found $i = 43^\circ$ and $\delta = 29^\circ$. The ASCA Fe Kα data was analyzed initially by Turner et al (1998) who found that $i_{\rm disk} = 15^\circ\,{}^{+9}_{-7}$. It was then reanalyzed by Weaver & Reynolds (1998) who consider an alternative model for the line profile and find that (for a Schwarzschild black hole) $i_{\rm disk} = 50^\circ\,{}^{+3}_{-4}$. On purely theoretical grounds, the results derived by Weaver & Reynolds (1998) are to be preferred, since they find values of $i_{\rm disk}$ for the four Seyfert 2 galaxies they analyze in the range $40^\circ \lesssim i_{\rm disk} \lesssim 50^\circ$. This is what one might expect for X–ray visible Seyfert 2 galaxies for which the line of sight to the nucleus must graze the edge of the hypothetical molecular torus. Thus we shall adopt $\phi = \pm 50^\circ$.

Using the radio position angle of 10° (Nagar & Wilson, 1999) we find by inspection of the HST image (Malkan et al. 1998) that the west side of the galaxy is closer to us. Note that although the radio source is a triple at the scale of about 100pc, it is evident that the northern lobe is the stronger on both 100 pc scales and 1 pc scales (Mulchaey et al. 1994). We conclude that the jet is seen in projection against the far side of the galaxy. Combined with the values given above, we derive $\beta \simeq 44^\circ$.

2.2.3. NGC3227

This is a Seyfert 1 galaxy for which Kukula et al. (1995) found that the radio jet is along the position angle -7°. The parameters determined by Mundell et al. (1995) using kinematical data are $i = 56^\circ$ and $\delta = 15^\circ$. Nandra et al. (1997) found that the Fe Kα line profile could be fitted by an inner disk inclination ($\pm\phi$) of $i_{\rm disk} = 20^\circ\,{}^{+10}_{-10}$. Using the rotation curve of this galaxy and assuming that the spiral arms are trailing we conclude that the east side of the galaxy is the nearer side, so the jet is projected against the nearer half of the galaxy. Using these values and Equation 3 we find that $\beta \simeq 63^\circ$. Notice that the accretion disk inclination found by Nandra et al. (1997) has large uncertainty so that our results should be taken with caution.

2.2.4. NGC3516

This is a Seyfert 1 galaxy for which Nagar et al. (1999) found that the radio jet is along the position angle 10°. The parameters derived by Kinney et al. (2000) are $i = 37°$ and $\delta = 46°$. Nandra et al. (1999) found that the Fe Kα line could be fitted by an inner disk inclination ($\pm\phi$) of $i_{\rm disk} = 35°\,^{+1}_{-2}$. The inspection of the HST image (Malkan et al. 1998) shows that the north side of the galaxy is closer, so the jet is projected against the nearer side of the galaxy. Applying Equation 3 to this data we find that $\beta \simeq 66°$.

2.2.5. NGC4051

This Seyfert 1 galaxy was observed in the radio by Ulvestad & Wilson (1984), and has a radio jet along the position angle 81°. Lizst & Dickey (1995) found from kinematical data $i = 39°$ and $\delta = 51°$. Fitting the Fe Kα ASCA spectrum, Nandra et al. (1997) found $i_{\rm disk} = 33°\,^{+5}_{-13}$. Using the rotation curve of the galaxy and assuming that the spiral arms are trailing, we find that the south west side of the galaxy is the nearer side so that the jet is projected against the side of the galaxy further from us. Using these values and Equation 3 we find that $\beta \simeq 23°$. Note again that the errors in the determination of $i_{\rm disk}$ are large so that the results should be taken with caution.

2.2.6. NGC4258

This is a Seyfert 2 galaxy for which Miyoshi et al. (1995) measured, using H_2O masers, the rotation curve of a circumnuclear disk with inner radius of 0.13pc. According to Miyoshi et al. (1995) , this disk is at an inclination relative to the line of sight ($\pm\phi$) of $i_{\rm disk} = 83°\,^{+4}_{-4}$. The inclination of the host galaxy is $i = 72°$, and the major axis position angle is 148°, determined by van Albada (1980) using HI kinematical data. Herrnstein et al. (1997) observed that the radio jet lies along the position angle 0°, which gives $\delta = 32°$. We find by inspection of the Digitized Sky Survey image that the west side of the galaxy is the nearer one, so the jet is projected against the farther side of the galaxy. Using Equation 3 and these values, $\beta \simeq 57°$.

Note that we have used the disk inclination derived from water maser measurements. However, the innermost ring at which the maser measurements are possible corresponds to several thousand Schwarzschild radii. We should bear in mind that the very inner disk at a few Schwarzschild radii (where the Fe Kα is emitted) might not be aligned with the disk at larger radii.

2.2.7. NGC5506

This Seyfert 2 galaxy was studied by Kinney et al. (2000), who found that the radio jet is extended along position angle 70°, $i = 82°$ and $\delta = 21°$. According to Wang et al. (1999) the Fe

Kα line of this galaxy can be fitted by an accretion disk with $i_{\rm disk} = 40^\circ\,^{+10}_{-10}$. From inspection of the HST image (Malkan et al. 1998) we find that the south side is the nearer side, so the jet is projected against the farther side of the galaxy. Using Equation 3 we find that $\beta \simeq 70^\circ$.

3. Discussion

We have shown that measurement of the three parameters δ, the projected angle between the galaxy major axis and the radio jet, i, the inclination of the galaxy disk, and $i_{\rm disk}$, the inclination of the inner accretion disk, together with the assumption that the radio jet is perpendicular to the inner accretion disk, yields (Equation 3) two possible values of the angle β, the angle between the radio jet and the plane of the host galaxy. In addition, the ambiguity between the two possible values of β can be resolved if one makes the additional assumption that the observed radio jet (for a one-sided jet, or in the case of a two-sided jet, for the stronger component) is closer to Earth than the host galaxy plane, and if one is able to determine whether the jet is seen in projection against the near side or the far side of the galaxy.

It is of some interest, however, that the method we have described above can fail. If the radio jet is seen to lie in projection against the nearer side of the galaxy to the Earth, then for a given pair of values of i and δ, the value of $\phi(< 0)$ must lie in the range $\phi_1 \leq \phi \leq 0$, where ϕ_1 is given by Equation 4. However, if, for such a galaxy, the value of the inner disk inclination $i_{\rm disk}$, derived from analysis of the X–ray data were to exceed $|\phi_1|$, we would have an inconsistency. This would imply that one (or more) of our assumptions had failed. Thus an important observational test of the assumptions underlying this analysis is to look for galaxies which might give rise to such a contradiction. Conversely, if, after measurements of a large sample of galaxies, none is found to show this inconsistency, we may begin to have confidence in the assumptions and the method. For the 7 galaxies measured for this paper, no inconsistencies have been found.

For those targets for which optical and radio data (i.e. δ and i) are already available, the most fruitful ones to pursue with X–ray observations in a search for self-consistency would be those galaxies with large inclinations i, with large values of δ, and (of course) whose radio jets lie in projection against the near side of the galaxy. An example of such a galaxy is the Seyfert 2, NGC 4388, for which $i = 70^\circ$, $\delta = 70^\circ$ (Kinney et al. 2000), and for which the jet is seen in projection against the near side of the galaxy. From Equation 4 we see that $\phi_1 = -21^\circ$. The galaxy was detected by ASCA (Iwasawa et al. 1997) but due to the large column density ($N_H = 4 \times 10^{23} cm^{-2}$) they detected only a narrow, gaussian shaped Fe Kα line and thus were not able to determine the accretion disk orientation (XMM-quality data may still be able to determine it). If we find this galaxy, as for the Seyfert 2s analyzed by Weaver & Reynolds (1998) has $i_{\rm disk} \simeq 40^\circ - 50^\circ > |\phi_1|$, we would have an inconsistency. However, for this galaxy, it might be that $i_{\rm disk} < 21^\circ$, and that it appears to be a Seyfert 2 because of the strong dust absorption seen in this nearly edge on galaxy, rather than because the inner disk (and molecular torus) is at a large angle to the line of sight. This is consistent with the detection of a gaussian Fe Kα line.

In a search for objects which might show inconsistency, the only targets for which X–ray analysis is already available, which are worth pursuing with radio observations, are those objects for which the sum of the measured inclinations of the galaxy disk and the inner accretion disk exceed 90°, that is for which $i + i_{\rm disk} > 90°$. For such galaxies, the inconsistency arises if the radio jet is observed to lie in projection against the near side of the galaxy, and if $\delta > \delta_{\rm max}$, where

$$\sin \delta_{\rm max} = \cot i \, \cot i_{\rm disk} \tag{5}$$

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We identify here two such galaxies, both Seyfert 2s, whose inner disk inclinations have been determined by Weaver & Reynolds (1998). They are:

• MCG -5-23-16, for which $i_{\rm disk} = 52°$, $i = 63°$ (de Vaucouleurs et al. 1991), and for which we find $\delta_{\rm max} = 23°$,

and

• NGC 7314, for which $i_{\rm disk} = 46°$, $i = 63°$ (de Vaucouleurs et al. 1991), and for which we find $\delta_{\rm max} = 29°$.

Both galaxies are unresolved by VLA (Ulvestad & Wilson 1984, Ulvestad, unpublished); sensitive VLBI observations will probably be necessary to determine a radio position angle.

4. Conclusion

We have described a method for determining the angle β the jet in a Seyfert galaxy makes with the normal to the host galaxy plane, and have applied the method to seven systems. The results are summarized in Table 1. [7] We note that the four Seyfert 1 galaxies have values for β of 23°, 62°, 63° and 66°, while the three Seyfert 2 galaxies have values of 44°, 57°, and 70°. The fact that no values are near 0° is consistent with previous conclusions that radio jets in Seyferts do not tend to align with the galaxy axes. We have also drawn attention to the method being able to give rise to an inconsistency, in which case we would be able to conclude *either* that the observed jet is on the far side of the host galaxy plane (as seen from Earth), *or* that the jet is not emitted perpendicularly to the accretion disk.

The launch of the X–ray observatories XMM and Chandra, coupled with optical and radio observations, should enable measurements of β to be made for a much larger sample of galaxies and with greater accuracy. This will open up the possibility for a better understanding of the geometry of the accretion processes around the active nucleus, and of the processes which give rise to the misalignment between galaxy disks and radio jets/inner accretion disks.

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[7] Given the quality, and the heterogeneous nature of the current data, we have not attempted a formal error analysis.

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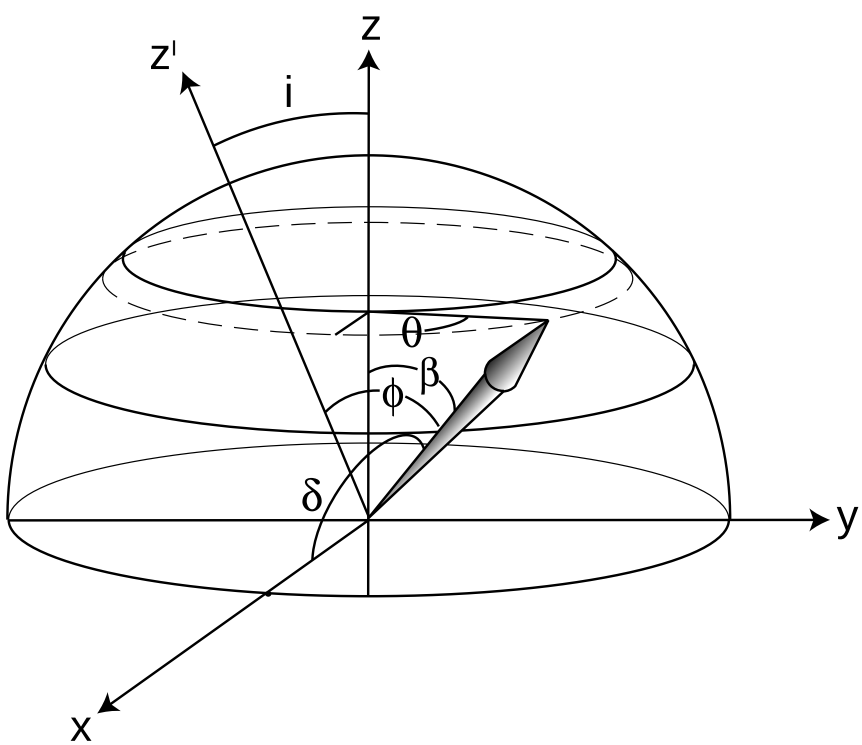

Fig. 1.— The galaxy lies in the XY plane, with coordinates placed so that the apparent major axis is the X axis and the galaxy axis is Z. The line of sight Z′, designed by the vector $\mathbf{k}_s$, is in the plane of the paper. The angle of inclination is i. The position angle between the apparent major axis of the galaxy and the radio jet projected onto the sky plane is δ. The radio jet, whose vector is given as $\mathbf{k}_j$, is designated by an arrow. The angle between the radio jet and the galaxy axis is β. The angle between the line of sight and the radio axis, commonly referred to as the opening angle of the active galaxy, is ϕ. For an accretion disk perpendicular to the jet, $\phi = \pm i_{\rm disk}$.

Table 1. Measurements and Results

Name	Type	δ	i	$i_{disk} = \|\phi\|$	β
MRK766	1	35°	31°	$34^\circ \pm 3^\circ$	62°
NGC3227	1	15°	56°	$20^\circ \pm 10^\circ$	63°
NGC3516	1	46°	37°	$35^{\circ}{}^{+1}_{-2}$	66°
NGC4051	1	51°	39°	$33^{\circ}{}^{+5}_{-13}$	23°
NGC2110	2	29°	43°	$50^{\circ}{}^{+3}_{-4}$	44°
NGC4258	2	32°	72°	$83^\circ \pm 4^\circ$	57°
NGC5506	2	21°	82°	$40^\circ \pm 10^\circ$	70°